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Evaluating measures for adapting the energy demand of a production system to volatile energy prices

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Abstract

Due to the increasing use of renewable energies and the volatile behaviour of wind and sun power new turbulences in energy markets – especially increasing and strongly fluctuating energy prices – are expected. Hence, companies' production systems have to be energy flexible in order to cope with these changes in energy markets. This paper presents an approach for evaluating measures for conducting energy flexibility, e.g. changing process parameters or rescheduling of processes depending on the availability of energy in the grid.

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Energy flexibility; energy efficiency; renewable energies; flexibility evaluation; demand response

1. Introduction

Due to the globalization of the economy, the rising speed of information transfer and the rapid emergence of new technologies [1] production systems are working in an environment that can be characterized as complex and uncertain [2] [3]. To cope with these uncertainties production systems have to be flexible [4]. Flexibility in this context describes the ability of a system to adapt itself with little penalty in time, effort, cost and performance to changes in the market environment [5]. Nowadays, production systems are faced with new turbulences in energy-markets. Due to the increasing use of renewable energy sources – especially wind power – prices are getting more volatile on energy markets depending on the current energy demand and energy generation as a consequence of weather conditions [6]. Based on these uncertainties new energy-contracts are forcing production systems to adapt their energy consumption to the actual energy availability in the grid [7]. Therefore, production systems have to be energy-flexible. In this context energy flexibility is defined as the ability of a production system to adept itself fast and without great expenses to changes in energy markets [8].

This paper presents measures which allow the adaptation of the energy demand of a production system to volatile energy prices. Next, parameters are explained which describe measures. Also the influence of volatile energy prices on these parameters is shown. Finally, a scheme for the evaluation of different energy flexibility measures is developed.

2. Volatile energy prices and energy flexibility

While electrical energy can't be stored economically in great amounts, energy grids have to be in balance at all times, i.e. the generation of energy has to be at the same level as the demand of energy in the grid. Due to the increasing use of renewable energies and the volatile behaviour of wind and sun power, energy gets not exactly generated when the customer needs it or does not need it. To maintain the balance of the energy grid the adaptation of the energy demand to the availability in the grid is a promising approach. This approach is known as Energy demand response in literature [9]. According to the U.S. Department of Energy demand response can be defined as followed [9]:

Demand response are changes in electric usage by end-use customers from their normal consumption patterns in

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response to changes in the price of electricity over time, or to incentive payments […] when system reliability is jeopardized.

As mentioned in the definition, demand response instruments can be categorized in two basic groups: the price-based demand response and the incentive-based demand response programs, see Fig. 1.

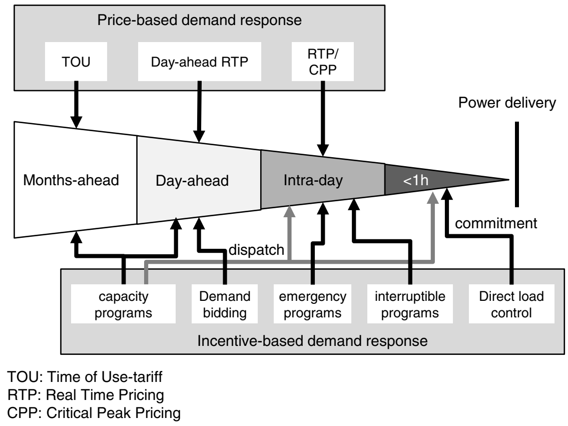

Fig. 1. Categorization of demand response instruments [9]

Price-based demand response gives customers time-varying rates that reflect the value and costs of electricity in different time periods, for example real-time pricing (RTP), i.e. prices varying every hour and reflecting market prices. These tariffs also can be more static like Time of Use (TOU) and Critical Peak Pricing (CPP) tariffs, where prices are fixed for longer blocks of time. With the information of the actual energy price, customers can decide whether they want to use less electricity at times when electricity prices are high or not.

The second group of demand response instruments is incentive-based. Customers can participate in these programs in addition to normal tariffs. By using incentive-based programs, participants receive a payment when reducing or enhancing its load at times requested by the program sponsor, triggered either by a grid reliability problem or high electricity prices. The different types of incentive based demand response instruments vary by the time the customer has in advance to commit his willingness to adapt his power demand and how the incentive payment is done.

The presented demand response instruments give production systems the opportunity to achieve energy cost savings compared to fixed price tariffs, when consuming less energy when energy costs are high and enhance energy demand when energy costs are low. This requires knowing the production systems' energy demand and possibilities to adapt it, i.e. production systems have to be energy flexible.

3. Evaluating measures for conducting energy flexibility

In this section measures for conduction energy flexibility will be presented. Next the influence of volatile energy prices on energy flexibility will be explained and a scheme for the evaluation of energy flexibility measures will be given.

3.1. Measures for conducting energy flexibility

The various flexibilities of a production system, like Routing-flexibility, Volume-flexibility or Process-flexibility allow adaptations of the production(-process), i.e. changes in the used machines and the amount and types of the produced parts, to cope with internal or external changes [5] [10]. While the energy demand of a production system is a result of the energy demand of its machines, adaptations of the production also lead to adaptations of the energy demand [11]. Therefore, energy flexibility is a result of the various flexibilities of a production system. Based on these considerations different measures for conducting energy flexibility can be found, see Table 1.

Table 1. Measures for conducting energy flexibility

Name	Description
Adaptation of process starts	Delayed or brought forward start of a process
Adaptation of machine scheduling	Production of a product on another machine
Adaptation of order sequence	Aligning the sequence of orders with a different energy demand to energy prices
Adaptation of staff free time	Aligning of staff free time to energy prices
Adaptation of shift times	Aligning of shift times to energy prices
Interruption of processes	Interruption of a running process and restart of the same process later
Adaptation of process parameters	Production of parts using different process parameters
Storage of energy	Saving of energy in energy storages, e.g. batteries
Changes in energy carrier	Switching of the energy carriers, e.g. using gas instead of electrical energy

One opportunity for aligning energy demand of production systems to volatile energy prices is the scheduling of processes [11]. If the workload of the production system is not at its maximum, the energy demand can be affected by delaying or pre-drawing processes. While different machines need a different amount of energy for the same task, the energy demand can also be changed by adapting machine scheduling. Also various jobs lead to different energy demands of the same machine and can consequently be adapted by changing the order sequence.

While the energy demand of a production system is often related with the operating time of its staff, the energy demand can be adapted by aligning staff free times and shift times to energy prices.

If the process technically allows it, the energy demand of a machine can be adapted by interruption of the running process or by producing parts using different process parameters, e.g. using different cutting speeds at a milling machine. Last but not least, the energy demand of a production system can be changed by saving electricity in an energy storage or by changing the energy carrier.

3.2. Influence of volatile energy prices on energy flexibility

In this section the influence of volatile energy prices on energy flexibility respectively on measures for conducting energy flexibility found in the previous section will be explained. Therefore, a German incentive-based demand response instrument – the so called “minute capacities” (German: “Minutenreserve”) – is used to illustrate the different time and cost requirements on energy flexibility measures.

The “minute capacities” are part of the German capacity program to stabilize the power transmission grid. To participate in minute capacities a load reduction or enhancement commitment has to be given one day ahead to the service provider. Beside the amount of the load, the customer is willing to reduce or increase, a basic price, a demand charge and a timeslot of four hours for the load reduction or enhancement has to be assigned.

In case of on an event in the energy grid the participants of “minute capacities” have to execute the committed load reduction or enhancement when the service provider gives a signal. The load reduction or enhancement then hast to be carried out not later than in 15 minutes. Then the load reduction or enhancement has to keep up until the service provider gives a second signal. This period of time can last between 15 minutes and 4 hours depending on the duration of the event in the energy grid. The redemption of the load reduction or enhancement then has to be executed again within 15 minutes. Therefore, the customer gets paid a demand charge for providing the load reduction or enhancement capacity and a basic price for the energy that has been shifted. The explained ideal cycle of “minute capacities” can be seen in Fig. 2.

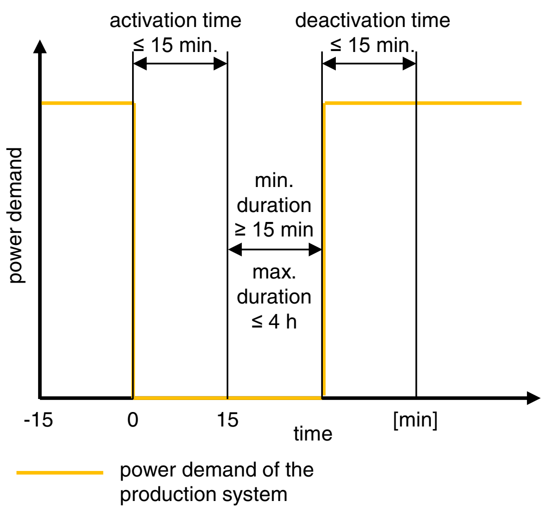

Fig. 2. Cycle of “minute capacities”

Based on the cycle of “minute capacities” different time and cost requirements on energy flexibility measures can be found. Measures therefore can be described with these requirements:

- Activation time
- Deactivation time
- Minimum duration
- Maximum duration
- Costs

The activation time specifies the necessary time until a load reduction or enhancement is fulfilled. As explained before, the load reduction or enhancement of a measure has to be carried out in a certain amount of time. In the example of “minute capacities” the activation time of a measure may not exceed 15 minutes. Hence, if the activation time of a measure is higher than 15 minutes the measure can’t be used for “minute capacities”.

The deactivation time is the time needed to take back a measure, i.e. to bring back the power demand level of a production machine or a production system to its original level, before the measure has been activated. This time – as the activation time of a measure – may also not exceed a certain amount of time.

After activation, the energy flexibility measure has to remain active at least for a minimum duration and can be used at most for the maximum duration. These time constraints of measures result from various technical or organicational constraints of the production machines and the production system, affected by the energy flexibility measure. While volatile energy prices change after a period of time, the minimum duration of the measure may not be too long and the maximum duration may not be too short. In the example of “minute capacities”, a measure with a maximum duration of three hours would not be useful for “minute capacities” as it could last up to four hours. Also a minimum duration of a measure of one hour also makes the measure useless for “minute capacities” while “minute capacities” can last only 15 Minutes. In this case the measure couldn’t be deactivated as the event would be shorter than the minimum duration of the measure.

By conducting a measure different costs can occur, e.g. costs for additional energy demand when changing process parameters of a production machine or inventory costs when shifting starts. While the main aim of energy flexibility is the reduction of energy costs, the costs of a measure may not exceed the savings due to cheap energy prices or exceed the payments in incentive-based demand response instruments.

3.3. Evaluation scheme

In this section a scheme for the evaluation of energy flexibility measures will be presented. Based on the five describing parameters of measures found in the section before, equations for evaluating each of these parameters are developed in this section. The equations should give values between 0 and 1, where 0 means that the measure does not fulfil the requirements of the energy pricing model and 1 means that all requirements have been fulfilled.

3.3.1. Evaluation of activation and deactivation time

Energy flexibility of a production system increases with a decrease of the activation and deactivation time of its measures. If the activation and deactivation time is higher than the required activation and deactivation time of the demand response instrument the measure gets useless for conducting energy flexibility. Therefore, the equation should give a value of 0. On the other hand shorter activation and deactivation times don't increase the value of a measure further. Hence, if the activation and deactivation times of a measure fulfill the requirements of the demand response instrument the equation should give back a value of 1. The factor α^{act} respectively α^{deact} which fulfills the identified requirements for the evaluation of the activation and deactivation time can be seen in equation 1 and 2, where t^{act} and t^{deact} are the activation and deactivation times of the measure. t_{bound}^{act} and t_{bound}^{deact} are the required activation and deactivation times of the demand response instrument.

$$\alpha^{act} = \begin{cases} 1, t^{act} < t_{bound}^{act} \\ \dfrac{t_{bound}^{act}}{t^{act}}, t^{act} \geq t_{bound}^{act} \end{cases} \tag{1}$$

$$\alpha^{deact} = \begin{cases} 1, t^{deact} < t_{bound}^{deact} \\ \dfrac{t_{bound}^{deact}}{t^{deact}}, t^{deact} \geq t_{bound}^{deact} \end{cases} \tag{2}$$

A graphical illustration of the equations 1 and 2 can be seen in Fig. 3.

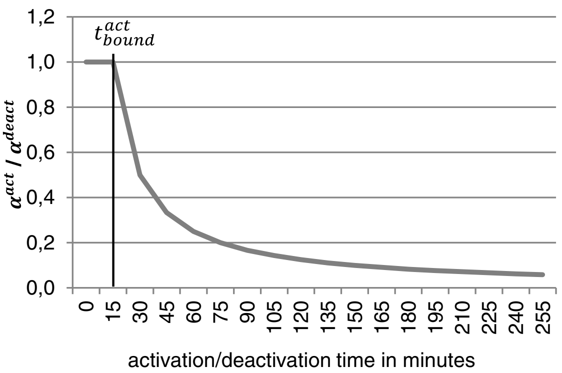

Fig.3. Evaluation of activation and deactivation time

3.3.2. Evaluation of minimal and maximal duration

In this section equations for the evaluation of the minimal and maximal duration of a measure will be presented. While volatile energy prices change after a period of time the minimum duration of a measure may not be too long. Otherwise the change of power demand of the production system due to a measure would persist while another change of energy price would require a deactivation of the measure.

If the maximal duration of a measure is too short, there may be the possibility that a cheap energy price level still exists while a measure has to be deactivated due to the maximal duration. A production system then loses the possibility to save energy costs based on the cheap energy prices.

It has to be mentioned that the required upper t_{bound_u} and lower t_{bound_l} boarder for the required minimal respectively maximum duration derive from the chosen demand response instrument. Therefore, the factors $\alpha^{\min}$ respectively $\alpha^{\max}$ for evaluating the minimum and maximum duration of a measure can be seen in equation 3 and 4, where $t^{\min}$ and $t^{\max}$ are the minimum and maximum duration of the measure.

$$\alpha^{\min} = \begin{cases} 1, t^{\min} < t_{bound\_l}^{\min} \\ 1 + \dfrac{1}{t_{bound\_l}^{\min}} - \dfrac{t^{\min}}{t_{bound\_u}^{\min} - t_{bound\_l}^{\min}}, t_{bound\_l}^{\min} < t^{\min} < t_{bound\_u}^{\min} \\ 0, t^{\min} > t_{bound\_u}^{\min} \end{cases} \tag{3}$$

$$\alpha^{\max} = \begin{cases} 1, t^{\max} < t_{bound\_l}^{\max} \\ \dfrac{t^{\max}}{t_{bound\_u}^{\max} - t_{bound\_l}^{\max}} - \dfrac{1}{t_{bound\_l}^{\max}}, t_{bound\_l}^{\max} < t^{\max} < t_{bound\_u}^{\max} \\ 0, t^{\max} > t_{bound\_u}^{\max} \end{cases} \tag{4}$$

A graphical illustration of the equations 3 can be seen in Fig. 4. The curve progression of equation 4 is equally to the one in Fig. 4, but it has a growing trend instead of a falling one.

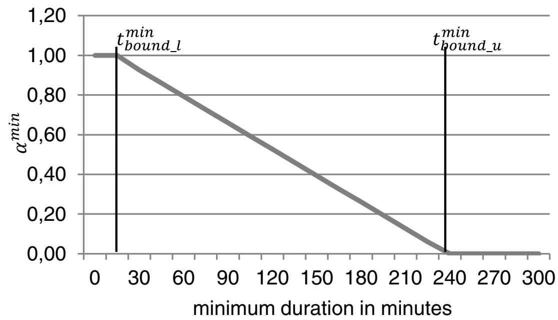

Fig.4. Evaluation of minimum duration

3.3.3. Evaluation of costs

As explained before, costs can occur when conducting a measure. Hence, a measure is only useful when its costs don't exceed the energy cost savings of the demand response instrument. While the saving potential depends strongly on the configuration of the different demand response instrument, this has to be considered when evaluating the costs of a measure. The difference between the price-based demand response and the incentive based demand response programs is, customers get paid an incentive payment in incentive based demand response programs. The saving potential of the price-based demand response tariffs is the possibility that customers can consume less respectively more electricity at times when electricity prices are high respectively low. Therefore, these two options have to be considered separately when evaluating the costs of a measure.

For every price-based demand response tariff an average energy price $\bar{k}^E$ can be found. For the energy spot market at the European Energy Exchange (EEX) the average energy price was 40,89 €/MWh in 2012 see Fig. 5.

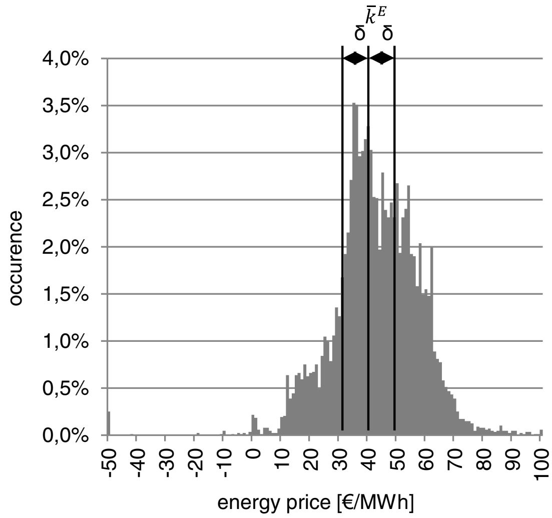

Fig. 5. Energy spot market prices on EEX 2012 [12]

It is assumed that a customer will not change his energy demand when energy prices are at an average level, i.e. are in a corridor δ of the average energy price. Customers will align their energy demand to the energy prices, when prices are below this corridor (consume more energy) or above (consume less energy). Therefore, the minimum saving potential per power unit $\overline{K}^E$ can be calculated with equation 5, where $\bar{t}^E$ is the average duration of a price level.

$$\overline{K}^E = \bar{t}^E \bar{k}^E \delta \tag{5}$$

Based on equation 5 the factor for evaluating the costs of a measure has to be 0 when the costs of a measure K exceed the energy cost savings, calculated with equation 5 and the power demand adaption of the measure ΔP. If the costs of the measure are smaller than the energy cost savings the factor has to grow to 1 when the total cost savings are growing, i.e. the ratio between the costs of the measure and the energy cost savings goes to 0.

While the main aim of energy flexibility is the saving of (energy) costs the evaluation of a measure depends on the different expectations of companies on the rate of return they receive from the conducting of a measure. Some companies may align their energy demand to energy prices even if they receive only little savings. Other companies may have great expectations on the cost savings of a measure. The individual expectations of companies on the rate of return they receive from measures have to be considered with a parameter r. It has to be set individually by the company at values bigger than 0.

The factor α^k for the evaluation of the costs of a measure in price-based demand response tariff can be calculated with equation 6.

$$\alpha^k = \begin{cases} 0, K > \bar{t}^E \bar{k}^E \delta \Delta P \\ 1 - \left(\dfrac{K}{\bar{t}^E \bar{k}^E \delta \Delta P}\right)^r, K \leq \bar{t}^E \bar{k}^E \delta \Delta P \end{cases} \tag{6}$$

The energy costs savings in an incentive-based demand response program are the incentive payments. These payments usually consist of two components, the reservation payments, determined by the offered load amount, and additional energy payments for the reduction. The energy costs savings per power unit in an incentive based demand response program can therefore be calculated with equation 7, where $\bar{k}_W^E$ is the average basic price and $\bar{k}_P^E$ is the average demand charge for the load reduction of enhancement.

$$\overline{K}^E = \bar{t}^E \bar{k}_W^E + \bar{k}_P^E \tag{7}$$

Following the same logic as the evaluation of the costs of a measure in a price-based demand response tariff, the factor for the cost evaluation in an incentive-based demand response program can be calculated with equation 8.

$$\alpha^k = \begin{cases} 0, K > \bar{t}^E \bar{k}_W^E \Delta P + \bar{k}_P^E \Delta P \\ 1 - \left(\dfrac{K}{\bar{t}^E \bar{k}_W^E \Delta P + \bar{k}_P^E \Delta P}\right)^r, K \leq \bar{t}^E \bar{k}_W^E \Delta P + \bar{k}_P^E \Delta P \end{cases} \tag{8}$$

A graphical illustration of equation 6 and 8 can be seen in Fig. 6, where r is set to 2.

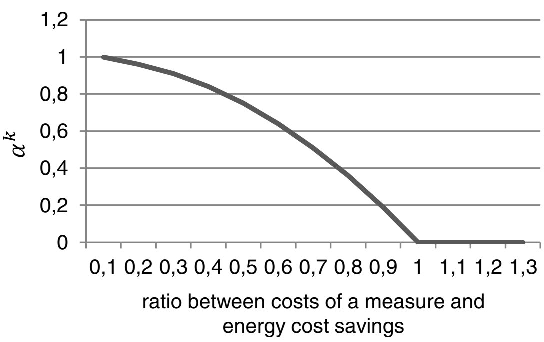

Fig. 6. Evaluation of costs

4. Application of evaluation scheme

In this section a short explanation about the use of the developed evaluation scheme is given. The evaluation scheme can be used for two purposes:

- Selection of measures
- Analysis of measures

4.1. Selection of measures

The aim of the selection of measures is to identify the most useful measures for conducting energy flexibility to reduce energy costs. These costs depend on the consumed energy amount. Therefore, measures which have the possibility to shift great loads – and as a consequence great amounts of energy – can lead to high energy cost savings. Though all time and cost requirements of the demand response instrument have to be fulfilled by the measure, expressed through the evaluation factors of the measure (see equations 1-5).

By multiplication of the power demand change of a measure with the evaluation factors of the measure a ranking order of all measures of a production system can be made and the selection of an appropriate measure can be done.

4.2. Analysis of measures

The second aim of the evaluation scheme is the analysis of the measures. As explained before all time and cost requirements of a demand response instrument have to be fulfilled by the measure. Hence, all time and cost evaluation factors have to return (almost) the value 1. For the analysis of the measure the single evaluation factors can be plotted in a net-diagram, see Fig. 7.

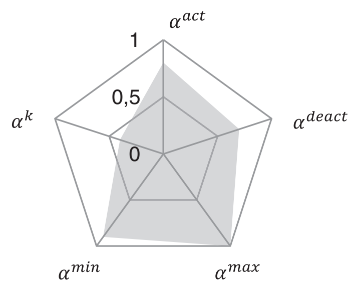

Fig. 7. Analysis of measures

The more the net-diagram is filled the more appropriate is the measure for conducting energy flexibility. The example in Fig. 7 shows, that there have to be considered technical or organizational optimizations for reducing the costs of the measure.

4. Conclusion and outlook

Due to the increasing use of renewable energy sources – especially wind power – prices are getting more volatile on energy markets. Based on these uncertainties different demand response instruments try to achieve changes in electric usage by end-use customers from their normal consumption patterns in response to changes in the price of electricity when system reliability is jeopardized. Therefore, production systems have to be energy flexible.

This work gives an introduction which measures can be used for conducting energy flexibility like the adaption of process starts, the adaption of machine scheduling or the adaption of an order sequence. Following, the parameters of energy flexibility measures, the activation time, deactivation time, minimum duration, maximum duration and costs of the measure were explained using the example of the German “minute capacities”. Then a scheme for the evaluation of measures based on the five describing parameters was presented and the application of the scheme for the selection and analysis of measures explained.

Based on this work future research has to investigate how energy flexibility of a production system can be evaluated. Especially the dependencies between different machines of a production system have to be considered in the evaluation of energy flexibility.

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